The Major Sources of the Cosmic Reionizing Background at $z \simeq 6$

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ABSTRACT

In this paper, we address which sources contributed most of the reionizing photons. Our argument assumes that the reionization ended around $z \simeq 6$ and that it was a relatively quick process, i.e., that there was a non-negligible fraction of neutral hydrogen in the Universe at somewhat earlier epochs. Starting from our earlier estimate of the luminosity function (LF) of galaxies at $z \simeq 6$, we quantitatively show that the major sources of reionization are most likely galaxies with $L < L_*$. Our approach allows us to put stronger constraints to the LF of galaxies at $z \simeq 6$. To have the Universe completely ionized at this redshift, the faint-end slope of the LF should be steeper than $\alpha = -1.6$, which is the value measured at lower redshifts ($z \simeq 3$), unless either the normalization (Φ_*) of the LF or the clumping factor of the ionized hydrogen has been significantly underestimated. If Φ_* is actually lower than what we assumed by a factor of two, a steep slope close to $\alpha = -2.0$ is required. Our LF predicts a total of $50 - 80$ $z \simeq 6$ galaxies in the HST Ultra Deep Field (UDF) to a depth of $AB = 28.4$ mag, which can be used to constraint both Φ_* and α. We conclude that the *least* luminous galaxies existing at this redshift should reach as low as some critical luminosity in order to accumulate the entire reionizing photon budget. On the other hand, the existence of significant amounts of neutral hydrogen at slightly earlier epochs, e.g. $z \simeq 7$, requires that the *least* luminous galaxies should not be fainter than another critical value (i.e., the LF should cut-off at this point).

Subject headings: cosmology: high-redshift — galaxies: luminosity function, mass function

1. Introduction

High resolution UV spectra of $z > 5$ quasars found in the Sloan Digital Sky Survey (SDSS) provide solid evidence that the intergalactic hydrogen was in a *completely ionized* state up to an early epoch of $z \simeq 6$ (e.g., Fan et al. 2001). At slightly higher redshifts, however, a small fraction of neutral hydrogen is being seen, as indicated by the complete Gunn-Peterson trough found in several SDSS quasars at $z = 6.28 - 6.43$ (Becker et al. 2001; Fan et al. 2003). This has been used to argue that $z \simeq 6$ marks the end of the reionization era, and that the redshift at which the reionization began may not be much higher than $z \simeq 6$ (Becker et al. 2001; Fan et al. 2002). Recently, Cen (2003) proposed that the Universe might have been reionized twice, where the first epoch was completed at $z \simeq$ 15–16 and the second epoch at $z \simeq 6$. The first reionization is consistent with an early beginning of reionization suggested by the recent Wilkinson Microwave Anisotropy Probe (WMAP) results (e.g., Spergel et al. 2003), while the second reionization is consistent with the SDSS results.

It is still not certain what kind of objects provided the reionizing background. Here we focus on the end of the reionization era at $z \simeq 6$. There seems to be a consensus that the AGN population is not sufficient to account for the entire required reionizing photon budget (e.g., Fan et al. 2002), which leaves *normal* star-forming galaxies as the only alternative. The discovery of $Ly\alpha$ emitters at $z \simeq 6.5$ (Hu et al. 2002; Kodaira et al. 2003) suggests that star-forming galaxies did exist at such early epochs, and the significant number of faint Lyman-break galaxy (LBG) candidates at $z \simeq$ 6–6.5 found by Yan et al. (2003a) suggest that these objects could indeed be responsible for the completion of the reionization at this epoch. In this letter, we further study the contribution of galaxies and AGN to the reionizing background, and point out that dwarf galaxies may well have contributed the vast majority of the reionizing photons. Our investigation provides significant constraints to the luminosity function (LF) of galaxies at $z \simeq 6$, most importantly the faint-end slope of the LF, and the critical luminosity of the *least* luminous galaxies that must have existed at $z \simeq 6$.

This paper is organized as follows. In §2, we summarize our current best knowledge of the LF of galaxies and AGN at $z \simeq 6$, which forms the base of our discussion. The contribution of these two types of objects to the total ionizing background is calculated in §3, followed by a discussion on the implications of our result in §4. A summary is given in §5. Throughout the paper, we adopt a cosmology of $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ $\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. The Luminosity Functions of Galaxies and AGN at $z \simeq 6$

Currently, the number of confirmed galaxies at $z \simeq 6$ is still insufficient to derive their LF in a conventional way. Yan et al. (2002) presented an *estimate* of the LF of galaxies at $z \simeq 6$ in terms of their cumulative surface density as a function of apparent magnitude. This estimate was made by using a Schechter function,

$$\Phi(M) = 0.921 \cdot \Phi_* \cdot 10^{0.4(\alpha+1)(M_*-M)} \cdot exp\left[-10^{0.4(M_*-M)}\right],$$

with the values of its three free parameters adopted as following: the characteristic absolute magnitude M_* (measured around rest-frame 1300Å) and the faint-end slope α obtained at $z \simeq 3$ (Steidel et al. 1996) were assumed to be the same at $z \simeq 6$, and the scale factor Φ_* was found by using the cumulative number density of $z \geq 5.5$ galaxies detected in the Hubble Deep Field North (HDF-N) as the normalization. In the cosmological model used in this paper, these three parameters are $M_{AB} = -21.03$ mag, $\Phi_* = 4.55 \times 10^{-4}$ Mpc^{-3} mag^{-1}, and $\alpha = -1.6$. The predicted cumulative surface density based on this estimated LF is reproduced here in Fig. 1 (red curves) with a few revisions.

All observational constraints available to date are also plotted in this figure for comparison. Among them, those based on the SDSS quasar hosts, the Keck $Ly\alpha$ emitters and the deep ACS parallel field were discussed in Yan et al. (2002; 2003a[1]). The three new upper limits at the bright-end are discussed in Yan (2003b). In short, the NOAO-4m MOSAIC LBG and $Ly\alpha$ limits are derived from a degree-sized intermediate-band survey centered on the HDF-North and South (Yan et al. 2003, in preparation), and the Subaru LBG limit is what we derived based on the deep Subaru data of the HDF-N (Capak et al. 2003). The data point marked as a cross is derived from the Large Area Lyman-Alpha (LALA) survey (Rhoads & Malhotra 2001; Rhoads et al. 2003). Recently, three more measurements have become available. Stanway et al. (2003a, b) used the public Great Observatories Origins Deep Survey (GOODS) single-epoch data to search for $z \simeq 6$ objects. Bouwens et al. (2003) searched for such objects in their deep ACS Guaranteed Time Obsevation (GTO) data. Most recently, the GOODS team released its $z \simeq 6$ candidate list derived from the stacked three-epoch ACS data (Dickinson et al. 2003). All these new observations agree with our $z \simeq 6$

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[1]Note that the survey depth quoted in Yan et al. (2003a) is incorrect. These ACS parallel data were taken at a gain of 4 e^-/ADU, and we corrected for this before applying the magnitude zeropoints that were measured at a gain of 1 e^-/ADU. However, this correction turns out to be unnecessary, since the HST on-the-fly pipeline already makes the extra step of dividing the gain value into the flat-fields, which is not documented in the obvious places. As a consequence, the magnitudes of the $z \simeq 6$ candidates reported in Yan et al. (2003a) should be 1.5 mag brighter than their quoted values. Fig. 1 has reflected this change, which makes the ACS parallel upper limit less restrictive. Other than these, the major conclusion in that paper remains unchanged. This change does not affect this current paper.

LF. The GOODS candidate catalog has sufficient statistics to allow us to derive not just one, but several constraints at different flux levels from 25.0 to 27.0 mag. All these values agree very well with our LF from 23.0 to 26.5 mag. At $m_{AB} > 26.5$ mag, the GOODS counts are significantly lower than our estimate, which is possibly due to the incompleteness of the catalog at the faint-end. To summarize, our LF broadly agrees with all known constraints, and is about the best that one can get with the available data so far.

For our purpose, an analytic form of the AGN LF is preferred. The "standard" double power-law quasar LF (e.g., Boyle, Fong & Shanks 1988) is therefore used:

$$\Phi(M) = \frac{\Phi_*}{10^{0.4(\beta_1+1)(M-M_*)} + 10^{0.4(\beta_2+1)(M-M_*)}}.$$

This form has been proved to be a very good representation for quasars up to at least $z = 2.5$. There are four free parameters involved: the turn-over magnitude M_*, the scaling factor Φ_*, the bright-end slope β_1, and the faint-end slope β_2. The SDSS has discovered 6 quasars at $z > 5.7$ in 2870 deg^2 to $AB = 20.2$ mag (see Fan et al. 2003). Using this as the normalization, and adopting $M_* = -23.9$ and $\beta_1 = -2.58$ (Fan et al. 2001), we obtain $\Phi_* = 1.53 \times 10^{-8}\, Mpc^{-3}\ mag^{-1}$. The biggest uncertainty is the faint-end slope β_2, which is essentially unknown for $z > 4$. Therefore three values, $\beta_2 = -1.58$, -2.0 and -2.58, are used. The first one is the value observed at $z \simeq 2-3$, the second one is the steepest value that we consider to be reasonable, and the last one is the limiting case ($\beta_2 = \beta_1$), which is considered for illustrative purposes only. The surface densities of AGN at $z \simeq 6$ calculated based on these parameters are superposed in Fig. 1 as blue curves.

3. Ionizing Background at $z \simeq 6$ and the Contribution of Galaxies and AGN

We first need to answer the following question: in order to keep the intergalactic hydrogen ionized at this redshift, what should be the critical ionizing photon emission rate per unit co-moving volume ($\dot{N}_{cri}$)? We can then find out if the integrated production rate of photons at $\lambda < 912$Å due to either AGN or galaxies meets this critical value.

A recipe of calculating $\dot{N}_{cri}$ has been given in Madau, Haardt & Rees (1999, their Eqn. 26; hereafter MHR99):

$$\dot{N}_{cri}(z) = 10^{51.2} \left(\frac{C}{30}\right) \times \left(\frac{1+z}{6}\right)^3 \left(\frac{\Omega_b h_{100}^2}{0.02}\right)^2 s^{-1}\ Mpc^{-3}, \qquad (1)$$

where C is the ionized hydrogen clumping factor. Choosing $\Omega_b h_{100}^2 = 0.02$, $C = 30$ and $z = 6$, one finds $\dot{N}_{cri} = 2.51 \times 10^{51}\, s^{-1}\ Mpc^{-3}$. As noted by MHR99, the time-dependent

clumping factor in this expression has be written in the form that is scaled to the value inferred at $z = 5$ from the numerical simulation of Gnedin & Ostriker (1997), which gave $C \simeq 30$ at $z = 5$.

The total ionizing photon production rate, $\dot{N}_i$, due to a given population of objects, can be related to its differential LF, $\Phi(M)$, via the following form (Yan 2003b) :

$$\dot{N}_i = B \int_{-\infty}^{M_{max}} 10^{-0.4(M+25+5logD_L)} \cdot \Phi(M)\ dM\ \ s^{-1}\ Mpc^{-3}, \tag{2}$$

where M is absolute magnitude (in the AB system) defined around rest-frame 1300Å, D_L is the luminosity distance (in Mpc) to the objects in question, and M_{max} is the absolute magnitude of the least luminous object that should be used in the integration. B is a constant whose value depends on the shape of the UV-SED of these objects, which can be represented by power laws. To be specific, $B = 6.886 \times 10^7 \cdot D_L^2 \cdot (0.65)^\delta/(k\gamma)$, where δ and γ are power-law indices (in the frequency domain) for $\lambda \leq$912Å and 912Å$\leq \lambda \leq$ 1400Å, respectively. The constant k is the continuum discontinuity factor across the Lyman limit at 912Å.

Following MHR99, we assume that the shape of the SED of a quasar has power-law indices of –1.8 at $\lambda \leq$ 1050Å and –0.8 at 1050Å$\leq \lambda <$2500Å, respectively. Using these values and the AGN LF described in §2, it is found that the contribution from AGN falls far short of the critical value $\dot{N}_{cri}$ for any reasonable faint-end LF slope (see also Lehnert & Bremer (2003) for their discussion at $z \simeq 5$). Integrated to $M = -16.0$ mag beyond which the existence of AGN activity becomes implausible, their total contribution are 0.004×10^{51} and 0.009×10^{51} s^{-1} Mpc^{-3} for the faint-end slopes of $\beta_2 = -1.58$ and -2.0, respectively. Even for the limiting case where $\beta_2 = -2.58$, the derived $\dot{N}_i$ value is only 0.055×10^{51} s^{-1} Mpc^{-3}.

Based on 29 LBG spectra at $z \simeq 3$, Steidel et al. (2001) measured the ratio of the continuum flux at rest-frame 1300Å and at the blue side of the Lyman limit to be ~ 4.6. This is equivalent to taking $(0.65)^\delta/k = 0.217$ in our expression for B, and is used hereafter. Note that by using this value, we implicitly adopt the Lyman continuum photon escaping fraction (f_{esc}) of Steidel et al. (2001), which is 10–13% in absolute terms. The index γ used in the following analysis was estimated by using a set of model spectra of galaxies with ages of 0.1 Gyr (Bruzual & Charlot 1993), and it was found that this SED slope is close to an equivalent power-law index of $\gamma \simeq 1.8$.

We find that the original LF estimate of Yan et al. (2002), which has a relatively shallow slope of $\alpha = -1.6$, cannot produce a large enough $\dot{N}_i$ that reaches $\dot{N}_{cri}$. This LF can account for about 67% of the critical value if Eqn. 2 is integrated to $M = -16.1$ mag,

but the integral increases only very slowly towards fainter magnitudes and never meets $\dot{N}_{cri}$, even when pushed to globular-cluster-type luminosities ($M \simeq -7$ mag). Modifying our LF by adopting a luminosity evolution scheme of L_*, such as $L_*(z) = L_*(z{=}3)(1+z)^\rho/4^\rho$, will not mitigate this problem, because the value of ρ is negative in a reasonable hierarchical structure formation model, and thus will make $M*$ fainter and the $\dot{N}_i$ value even less.

Thus we explore other steeper α values to see if $\dot{N}_{cri}$ can be met at a reasonable minimum luminosity. We consider $\alpha = -1.7, -1.8, -1.9$, and -2.0, where the steepest one is the critical value at which the integral of a Schechter function diverges if the integration is carried to infinitely low luminosity. For these slopes to meet the normalizing condition (cumulative surface density of 1.37 per arcmin^2 to $m_{AB} = 27.0$ mag; see Yan et al. 2002), Φ_* has to be 4.27, 4.00, 3.74, and $3.49 \times 10^{-4} Mpc^{-3}$, respectively. We find that $\dot{N}_{cri}$ can be reached at the following critical absolute magnitudes for the above slopes, respectively: M = –8.8, –14.6, –15.8, and –16.6 mag (at $z \simeq 6$ these corresponds to apparent magnitudes of 37.9, 32.1, 30.9, and 30.1 mag, respectively). In other words, the *least* luminous galaxies that the Universe should have produced by this redshift should be at these magnitude levels or fainter in order to have a fully ionized Universe at $z \simeq 6$. These results are shown in Fig. 2 (top panel).

4. Discussion

The quantitative results above depend on three factors, namely, the clumpiness of ionized hydrogen (C), the scaling factor of the LF of galaxies (Φ_*), and the escaping fraction of Lyman continuum photons (f_{esc}). The first one affects the value of $\dot{N}_{cri}$, while the last two affect $\dot{N}_i$.

The value of $\dot{N}_{cri}$ scales linearly with the clumping factor C. In Eqn. 1, this clumping factor is scaled to its value at $z = 5$. We followed MHR99 and adopted $C = 30$, which is suggested by the numerical simulations of Gnedin & Ostriker (1997). Should C drop to $\sim$ 20, $\dot{N}_{cri}$ would drop by 1/3, and a faint-end slope steeper than $\alpha = -1.6$ would no longer be required, since now $\dot{N}_i$ would reach the critical absolute magnitude at $M = -16.1$ mag. Similarly, steeper slopes, α = –1.7, –1.8, –1.9, and –2.0 would make $\dot{N}_i$ reach the critical absolute magnitude at M =–17.0, –17.4, –17.7, and –17.9 mag, respectively.

The value of $\dot{N}_i$ scales linearly with the scaling factor Φ_* of the LF. Since increasing $\dot{N}_i$ has the same effect as decreasing $\dot{N}_{cri}$, we get exactly the same answers as above, if the scaling factor increases by a factor of 1.5. Since $\dot{N}_i$ also scales linearly with f_{esc} (assuming it is not a function of luminosity), the same answers hold if f_{esc} increases by the same factor. On the other hand, if either Φ_* or f_{esc} drops by 1/3, a faint-end slope steeper than –1.8 is

necessary to reionize the Universe. In this case, $\dot{N}_{cri}$ can be reached at $M = -12.5$ and –14.7 mag for a slope of –1.9 and –2.0, respectively. Smaller Φ_* or f_{esc} requires the LF extend to fainter luminosity; however, if either of them is smaller by a factor of two, only $\alpha = -2.0$ can meet the reionization requirement.

These values give the critical luminosity that the least luminous galaxies should have, i.e., a lower limit to M. By considering the additional constraint that the intergalactic hydrogen at slightly earlier epoch still had a non-negligible neutral fraction, we can further improve these limits into two-sided luminosity ranges. Cen (2003) gave a detailed modeling of the evolution of intergalactic medium in the double-reionization scheme, and the neutral fraction inferred from this modeling is about 15% at $z \simeq 7$. The precise neutral fraction at a specific redshift does not matter too much for our purpose; the point is that at an earlier epoch, e.g. at $z \simeq 7$, the total ionizing photon production rate of galaxies should not exceed the critical value such that a significant amount of neutral hydrogen can still exist, otherwise no GP-trough would be seen at $z \simeq 6$.

The calculation can be performed similarly to that described in §3. To first order, we can assume that there is no evolution in the LF during the relatively short time period from $z = 6$ to 7, which is only 0.16 Gyr. At $z = 7$, $\dot{N}_{cri} = 3.75 \times 10^{51}$ s^{-1} Mpc^{-3} for the nominal C value of 30. Now the requirement is $N_i < N_{cri}$. If nothing else changes, a LF faint-end slope of –1.8 or shallower will satisfy this criterion. Steeper slopes of α = –1.9 and –2.0 require that the LF truncates before it reaches M = –12.5 and –14.6 mag, respectively. The bottom panel of Fig. 2 demonstrates these results.

If $C = 20$, or equivalently if either Φ_* or f_{esc} is increased by a factor of 1.5, it requires that the LF truncates before it reaches M = –12.4, –15.8, –16.9, and –17.5 mag for slopes of –1.7, –1.8, –1.9, and –2.0, respectively (a cut-off is not required for a slope of –1.6). On the other hand, if either Φ_* or f_{esc} is decreased by 1/3, or equivalently if $C = 45$, slopes of –1.9 and –2.0 require the LF truncate before it reaches M = –4.4 and –11.8 mag.

Table 1 summarizes these results. We note that case a) is what we believe to be the most plausible, given our best knowledge about the relevant parameters. Case b) and c), on the other hand, explore a wider parameter space. However, we point out that case b) is not very likely for several reasons. First, the clumping factor is not likely to be as low as 20, since the nominal value of $C = 30$ obtained by Gnedin & Ostriker (1997) might already have underestimated the true value because of the finite resolution of their simulation. Second, the scaling factor of the LF, Φ_*, is not likely to be significantly higher than the value suggested in Yan et al. (2002), otherwise all the recent searches for $z \simeq 6$ objects would have resulted in more bright (z-band $m_{AB} \leq 26.0$ mag) candidates than what have been actually observed. Third, the Lyman photon escaping fraction of star-forming galaxies is not likely to be much

higher than $\sim$ 10–13%, given that such a value already seems to be rather high (cf. Giallongo et al. 2002).

The Ultra Deep Field (UDF) campaign of the ACS/HST (http://www.stsci.edu/hst/udf), whose data are now being taken and will be released to the public in February 2004, will greatly narrow down the range of α. Depending on its the real value, we predict a total of 50 to 80 genuine $z \simeq 6$ objects in the UDF to its designed 10 σ depth of 28.4 mag.

5. Summary

In this paper we investigate the major sources of reionization at $z \simeq 6$ based on the best available observational constraints. Using the LF estimate proposed for galaxies at this redshift (Yan et al. 2002) as the starting point, we find that *normal* galaxies can account for the entire reionizing background, provided that the faint-end slope of their LF is steep enough and that the LF extends to sufficiently low luminosity. We explore a range of faint-end slopes, from $\alpha = -1.6$, a value that the LF has at $z \simeq 3$, to $\alpha = -2.0$, the critical value at which the integration of a Schechter LF diverges. We find that dwarf galaxies, rather than their more luminous counterparts or AGN, produced the vast majority of the reionizing photons at $z \simeq 6$. Using the best estimate of the relevant parameters, we find that the faint-slope of the LF of galaxies at $z \simeq 6$ should be steeper than –1.6, if the adopted Φ_* holds, or as steep as $\alpha = -2.0$ if Φ_* is lower by a factor of two. In addition, we show that the least luminous galaxies should be fainter than a certain critical luminosity, whose exact value depends on the actual faint-end slope. Furthermore, by requiring that there still was a non-negligible neutral hydrogen fraction at slightly earlier epochs ($z \simeq 7$), we point out that the LF should truncate at a certain luminosity threshold, whose value again depends on the actual faint-end slope. The HST UDF data will be able to narrow down the range of this important parameter, whose precise value is obviously important for planning the performance of the James Webb Space Telescope.

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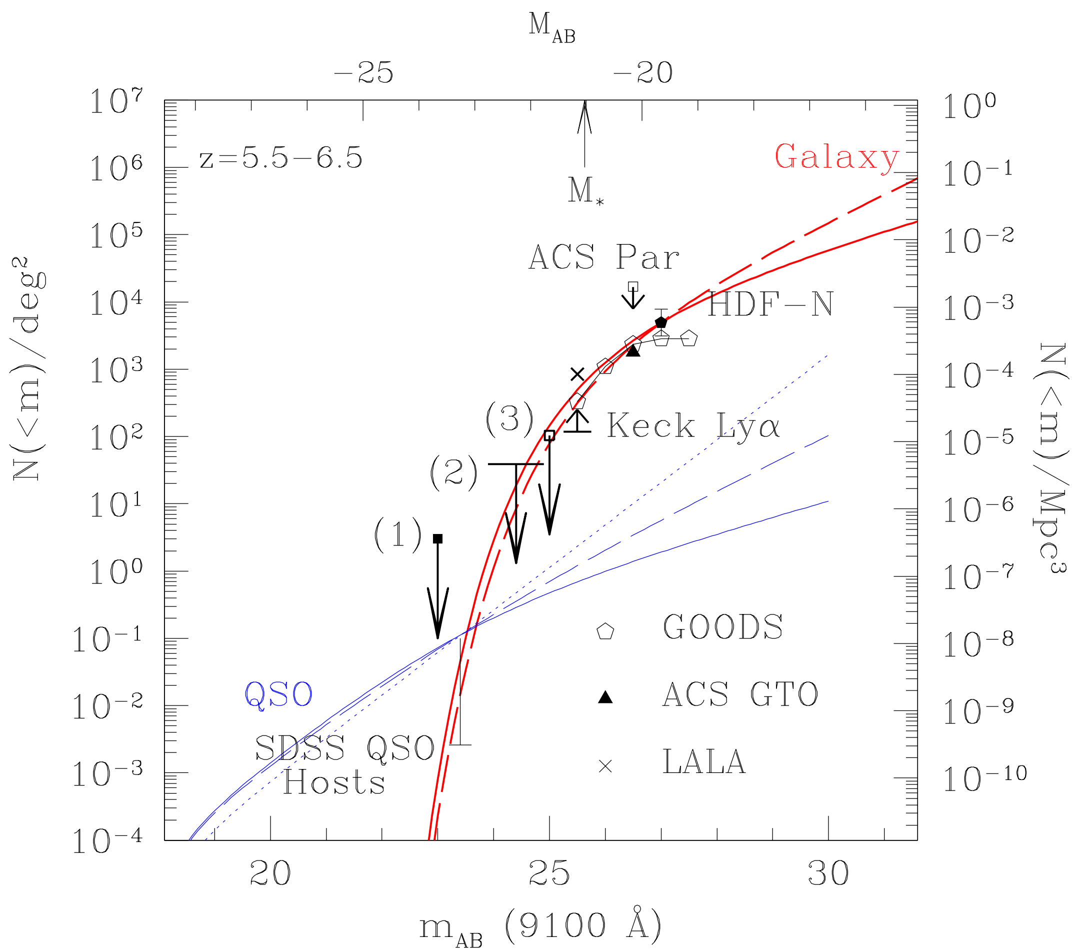

Fig. 1.— The best estimate of the LF of galaxies at $z \simeq 6$ (red curves), based on Yan et al. (2002), agrees with all known observational constraints. Two faint-end slopes, $\alpha = -1.6$ (solid line) and -2.0 (long dashed line), are shown. Only new constraints are discussed here. The upper limits marked (1) and (2) are derived from a degree-sized intermediate-band survey (Yan et al. 2003, in preparation), while the one marked (3) is derived based on the deep Subaru data of Capak et al. (2003). The cross is derived from the LALA survey (Rhoads et al. 2003). The solid triangle is based on Bouwens et al. (2003). The open pentagons connected by line are based on the results of the GOODS (Dickinson et al. 2003). The upper limit based on the ACS parallel observation of Yan et al. (2003a) has been corrected to $AB = 26.5$ mag to account for the proper magnitude zeropoint. This LF predicts that 50–80 $z \simeq 6$ objects will be found by the UDF campaign. For comparison, the blue curves show the expected number density of quasars at $z \simeq 6$, derived by using a double-power law LF and the normalization based on the SDSS $z \simeq 6$ quasar sample. Three different faint-end slopes are assumed, $\beta_2 = -1.58$ (solid curve), -2.0 (dashed curve), and –2.58 (dotted line). A truncation at $M = -16$ mag is applied, as beyond this point the existence of significant AGN activity is implausible.

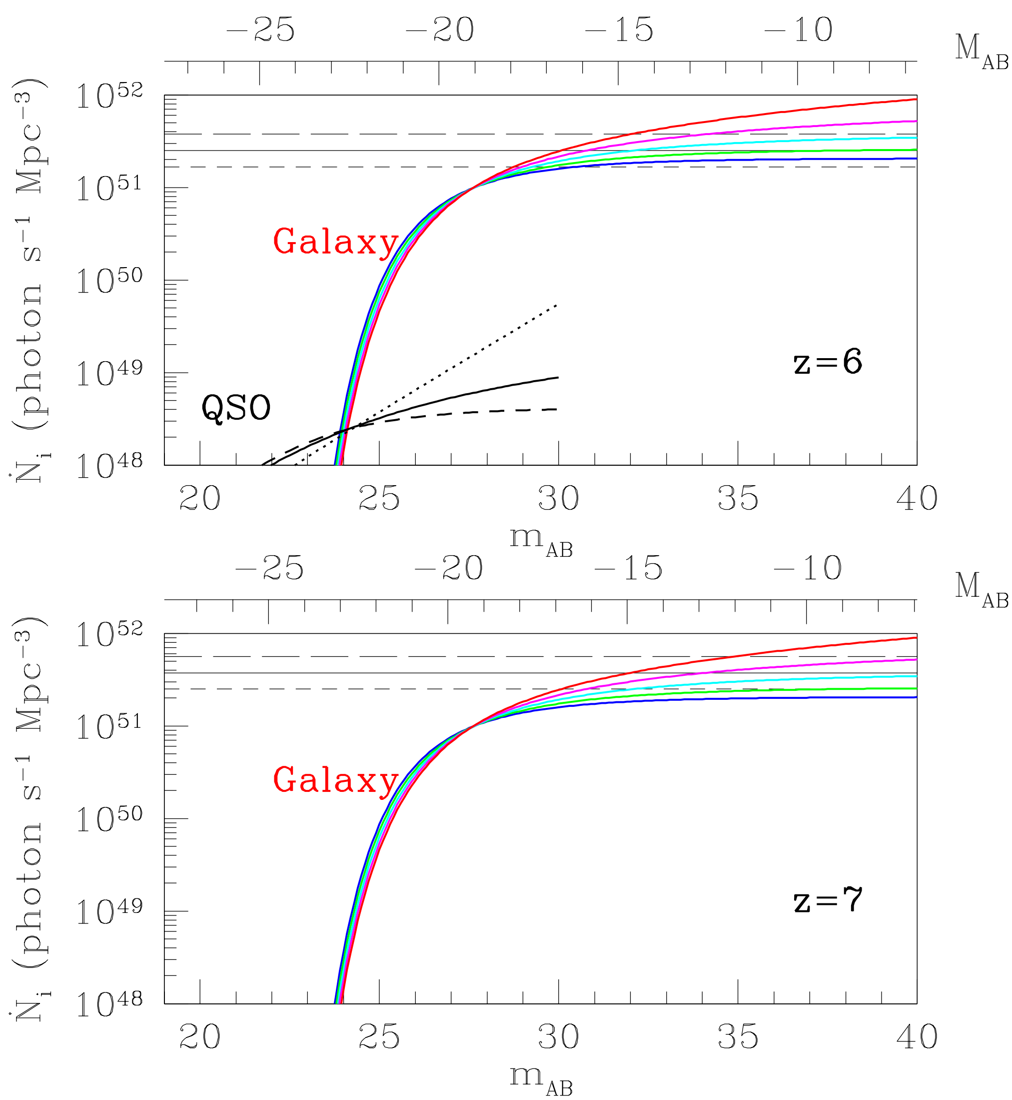

Fig. 2.— (Top) At $z \simeq 6$, the reionizing photon production rate due to galaxies should meet the critical value in order to keep the Universe fully ionized. The solid, long-dashed and short-dashed horizontal lines are the critical values if the clumping factor (at $z = 5$) $C = 30$, 45 and 20, respectively. The contribution from galaxies is shown in color, assuming different faint-end slopes of their LF: –1.6 (blue), –1.7 (green), –1.8 (cyan), –1.9 (magenta), and –2.0 (red). Galaxies can account for the entire reionizing photon budget provided that their LF is sufficiently steep ($\alpha \leq -1.7$), and extends to sufficiently low luminosity. Quasars can only contribute an insignificant fraction of the ionizing photons, as the black curves show: the solid, long-dashed and dotted lines are for faint-end slopes of –1.58, –2.0 and –2.58, respectively. (Bottom) The reionizing photon production rate due to galaxies at a slightly earlier epoch should be smaller than the corresponding critical value, as there was still a significant fraction of neutral hydrogen. The case is shown for $z \simeq 7$. Legends are the same as in the top panel. The LF of galaxies should cut-off at a certain luminosity, i.e., there is a luminosity threshold for the *least* luminous galaxies at this redshift, below which the LF cannot continue or it would leave no neutral hydrogen at $z \simeq 7$ and no GP-trough in SDSS quasars at $z > 6$.

Table 1: The luminosity range of the least luminous galaxies that should exist at reionization

α	$\Phi_*^\dagger$	${M_{min}}^{\rm a}$	${M_{min}}^{\rm b}$	${M_{min}}^{\rm c}$
–1.6	4.55	N/A	$-16.1 \leq M_{min}$	N/A
–1.7	4.27	$-8.8 \leq M_{min}$	(–17.0, –9.1)	N/A
–1.8	4.00	$-14.6 \leq M_{min}$	(–17.4, –14.6)	N/A
–1.9	3.74	(–15.8, –12.6)	(–17.7, –15.9)	(–12.5, –4.4)
–2.0	3.49	(–16.6, –14.7)	(–17.9, –16.6)	(–14.7, –11.8)

[†]Nominal scaling factor of the LF (in unit of $10^{-4} Mpc^{-3}$) by forcing an accumulative number density of 1.37 per arcmin^2 to $m_{AB} = 27.0$ mag (Yan et al. 2002).

[a]For the case where $C = 30$, and Φ_* and f_{esc} have their nominal values (see text). The minimum absolute magnitudes are referred to rest-frame wavelength at around 1300Å, and are in the AB system.

[b]For $C = 20$, or equivalently either Φ_* or f_{esc} increased by a factor of 1.5.

[c]For $C = 45$, or equivalently either Φ_* or f_{esc} decreased by 1/3. If Φ_* decreases by a factor of two, only $\alpha = -2.0$ can meet the reionization requirement.